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ART. I. — 1. *Études sur les Glaciers.* Par LOUIS AGASSIZ. Neufchatel. 1840.

2. *Essai sur les Glaciers et sur le Terrain Erratique du Bassin du Rhone.* Par JEAN DE CHARPENTIER. 1841.

3. *Occasional Papers on the Theory of Glaciers, now first collected and chronologically arranged. With a Prefatory Note on the Recent Progress and Present Aspect of the Theory.* By JAMES D. FORBES, D. C. L., F. R. S., Professor of Natural Philosophy in the University of Edinburgh. Edinburgh: Adam and Charles Black. 1859. 8vo. pp. 278.

4. *The Glaciers of the Alps. Being a Narrative of Excursions and Ascents, an Account of the Origin and Phenomena of Glaciers, and an Exposition of the Physical Principles to which they are related.* By JOHN TYNDALL, F. R. S., Professor of Natural Philosophy in the Royal Institution of Great Britain, and in the Government School of Mines. With Illustrations. Boston: Ticknor and Fields. 1861. pp. 446.

"THE speculations of the natural philosopher," says Sir John Herschel, "however remote they may for a time lead him from beaten tracks and every-day uses, being grounded in the realities of nature, have all of necessity a practical application." Students of natural philosophy are too often condemned as useless speculators by that large class of so-called practical and common-sense persons who see no value in any

pursuit not directly productive of material advantage. Pure science is one thing, applied science another; and we must no more expect a single man to cultivate both, than that the judge having interpreted the law shall descend and execute the details of police duty. Some must perfect tools, while others apply them to daily use; and some must devote themselves to the study of those natural phenomena which make us acquainted with the causes whence proceed the effects upon which our worldly labors depend. It is easy enough to appreciate science when we see it applied to art; but enlightened philosophical liberality will acknowledge and encourage the science before the art is born.

No branch of study will place us in closer connection with the workings of nature, or in a better position to observe how the most delicate physical elements combine to produce the most stupendous results, than that which concerns those vast masses of ice, the glaciers, which, descending from the snow-fields of the higher Alps with slow but irresistible march into the lower valleys, overwhelming villages, mowing down forests, damming rivers, ploughing up the soil, and grinding, grooving, and polishing the rocks over which they pass, finally present the apparent anomaly of a mountain of perpetual ice surrounded by orchards and pastures and fields of grain.

The appearance of the intensely interesting book of Professor Tyndall has induced us to present a brief review of the several glacial theories which have been put forth since 1840, with an exposition of the present state of the question, considered as a matter of physics. We say as a matter of physics, for as such the *cause* of glacier motion must be regarded; although the geologists were the first to enter this field of research, and the *effects* of glacial action, as seen in the modification of surface geology, certainly belong to that science. Of the geological agency of the glaciers in the past and present we do not propose to speak, but refer to the works of Charpentier and Agassiz.

In the ordinary economy of nature, the water which descends from the clouds as rain is disposed of in three ways; — first, by being absorbed into the soil; secondly, by evaporating into the air; and thirdly, by flowing off from the high

lands to the lower in the form of rivers, by which it is carried to the sea, again to be taken up into the air, thus completing the circuit. That these several operations may take place, the water must be liquid. Below a certain temperature the moisture held by the clouds cannot remain liquid, but takes the form of frost, snow, hail, or ice. As we ascend above the surface of the earth, the air becomes colder and colder, so that above a certain line no rain can fall; but whatever the clouds deposit will be snow or hail. Science has shown why the higher are colder than the lower regions, although they are nearer to the source of heat. A portion of the sun's rays strike the earth and are absorbed by it; but another portion are reflected, and serve to warm the atmosphere by which the globe is surrounded. Now the nature of the warm rays from the sun is so modified by their contact with the earth, that, while they find no obstacle in passing down through the atmosphere, they are almost entirely prevented from ascending. This heat descends all day, and so accumulates in and about the earth in a quantity sufficient to prevent any great fall of temperature during the night. As we ascend above the surface, we leave this atmospheric belt beneath us, and with it the warmth confined therein; and at a certain elevation we have little except the direct heat from the sun, which is not sufficient to reduce the snow that falls in these high regions to water. The line above which the snow remains unmelted is, at the equator, from 16,000 to 18,000 feet high. In the polar regions, however, we have a different condition of things. The sun does not rise high at any time, and very little heat is received from it. In the high latitudes snow and ice remain all the year round at the sea level. Thus there are two ways in which we may have what is called perpetual snow, — by going up from the surface, or by going north. Between the equator and the polar circle the snow line diminishes in height as the latitude increases. We shall now be asked, What becomes of the matter deposited by the clouds above the snow line? Why does it not accumulate indefinitely upward? The existence and operation of the glaciers give at once an answer to the question, and, while showing us the process which nature uses to compensate for an ex-

traordinary degree of cold in the present, at the same time point back to a period when that process by a much greater action represented a correspondingly lower temperature, at least over certain parts of our globe.

What the glaciers are may be best seen by a description of one. The group of mountains of which Mont Blanc is the highest peak encloses a vast irregular basin, the average elevation of which is 9,000 feet above the sea, while the surrounding summits rise from 3,000 to 6,000 feet higher. This enclosure is connected with the valley of Chamouni by a long crooked gorge, varying in width from one half to three fourths of a mile, bounded on either side by steep walls of rock, and so inclined that the lower end, where it opens into the valley, is about 3,500 feet above the sea. Let us suppose that we have descended from the mountains, and stand within this great basin. We find ourselves in the midst of a broad sea of snow, the shores of which are steep walls of rock, in some places covered with shining drifts, and in others bare. This snow, as it falls, is generally dry and powdery; but it afterwards changes into a mass of rounded grains of ice, or granular snow, called by the Swiss *Alps-névé*. The cause of this change will be noticed soon. On going out from the basin, we find the granular snow becoming gradually consolidated, and finally giving place to a sort of incompact ice. As we pass down, and get fairly into the narrow gorge, this grows more dense, and comes at last to be hard, brittle, and transparent. We stand, in fact, upon a frozen river, reaching from shore to shore, and having a depth of from 500 to 1,000 feet. As we approach the valley of Chamouni, we are far below the line of perpetual snow, and when we reach the end of our ice-river we find ourselves surrounded by green forests and pastures, with flowers in full bloom. Thus the glacier at its source in the high mountains is a mass of powdery snow, which changes by insensible degrees to a river of solid ice, protruding far below the perpetual-snow line into the cultivated valleys beneath.

The most superficial reader will now ask how this body of ice can maintain its solidity far below the line of perpetual snow, and subject to warm rains and warm weather; for it is

a fact that in many cases glaciers do not decrease, but absolutely increase, — indeed, examples are not wanting of their advancing so far as to sweep away houses, and to encroach on the farms in the low lands. The answer brings us at once to the most interesting fact connected with the whole subject. Strange as it must seem to one who stands upon the river of ice, apparently as rigid as the rocky walls that bound it, the whole mass of the glacier *moves* bodily down the gorge. We have the most ample proof of the nature and amount of this movement. For the present let the following facts suffice. In 1827, M. Hugi built a cabin upon the Lower Aar glacier; in 1860, this cabin was about two miles below the point where it was erected. In 1820, Dr. Hamel lost three guides by an avalanche upon the glacier of Bossons, half-way up Mont Blanc; in 1861, the remains of one of them were found in the valley of Chamouni at the lower end of the glacier. In 1836, a knapsack was lost on the Talèfre glacier, 8,657 feet above the sea; in 1846, the same knapsack was found at an elevation of 7,512 feet, and 4,300 feet from its first position. We may now answer briefly the question, What are the glaciers? by defining them as masses of ice which, originating in the great mountain basins above the line of perpetual snow, move down into the warm regions, and, giving birth to streams of water at their lower extremities, provide the means for that circulation which plays so vital a part in all the operations of nature. Having now this general understanding, let us descend to particulars, and look at the data which have been collected with the view of explaining the formation and action of the glaciers.

We have spoken of the perpetual snow line. By this term is meant the height at which the annual fall of snow is just melted, and no more. Below this the melting is more than the supply, above it the supply more than can melt; though it is not to be supposed that no melting goes on above this line, any more than that no snow falls below it. Some melting takes place even on the highest Alpine peaks, inasmuch as the snow which falls there is generally changed to ice, at least superficially. Were the surface of the earth a uniform plain,

capable of absorbing in all places the same quantity of solar heat, the temperature at any place would be simply as the latitude; and the parallels of latitude would be isothermic lines. The division of the surface of the globe, however, into land and water, mountain and plain, and the operation of various winds and atmospheric currents, cause the lines of equal temperatures to be quite irregular, and to depart very far from the parallels of latitude. The mean temperature of Boston is much lower than that of Rome, although the latitude is very nearly the same. The mean temperature of Washington is very nearly the same as that of London, while the latter place is a dozen degrees north of the former. The elevation of the snow line above the sea is in like manner somewhat irregular, although generally dependent upon the latitude. In Norway it is from 3,000 to 5,000 feet; in the Swiss Alps, from 8,000 to 9,000; and in the Himalayas and the Andes, from 16,000 to 18,000 feet. From this it follows that a group of mountains in one country may produce glaciers, while a group in some other land equally high, and even of the same latitude, shall produce none. The elevation of the snow line in different parts of the world, and the geographical location of the glaciers, may be found well defined in Johnston's Physical Atlas. We will take room here merely to say that they occur in the north and south polar regions, in Spitzbergen, Lapland, Iceland, Norway, in the Pyrenees and the Alps, in the Caucasus, the Altai and the Himalaya Mountains. The icebergs of the Arctic and Antarctic Seas are indeed fragments of enormous glaciers, which, descending from the snowy mountains of the polar continents, break off, and, floating away, reach a climate warm enough to melt them, thus completing the circulation already referred to. A low temperature, though essential to the formation of glaciers, does not alone suffice to produce them. Many high peaks which rise far above the snow line never bear glaciers. It is to the orographic structure, or to the shape and arrangement of a mountain group, that the power of producing large glaciers is to be attributed. The great enclosed basins are an essential feature, but they must be elevated into the region of perpetual snow. When

these conditions are combined, and a low mean temperature is added, we may be sure of a large glacier.*

For convenience in treating of glaciers, they have been generally divided into two orders. Those of the first order lie in the deep valleys, have an inclination of only from 3 to 10 degrees, and are fed by large basins. Those of the second order lie on the flanks of mountains, incline from 15 to 50 degrees, and are not fed by large basins. These last, when they lie upon the sides of a valley enclosing a glacier of the first order, often move down, and, welding themselves to the main trunk, become tributary thereto. The glacial surface is far from being clean and white, like the ice of a frozen river. That part which lies above the snow line, and which has not yet become compact ice, is tolerably uniform and clean; but the lower part, or the glacier proper, is loaded with the rocks and dirt brought down by slides and avalanches from the sides of the valley, and traversed by huge rents called crevasses. The *débris* thrown from the mountains accumulates along the edge of the glacier, until it amounts to a continuous ridge or train of rocks and gravel. Even if there are places where the slopes are so firm as not to break and slide, the motion of the glacier brings each point in succession to those places which furnish material, and thus the continuity of the moraine is preserved. Those trains of rocks which form upon the shores or edges of the glacier are called lateral moraines. We find, however, similar trains in many cases in the central part of the ice, while between the sides and centre the surface will be comparatively clean. This phenomenon is at once explained by following the central or medial moraine towards the source of the glacier. At some point the medial moraine is sure to divide or split lengthwise, each half becoming a lateral moraine for one of the two branches of which the trunk-glacier which has a medial moraine is always composed. Whenever two branches come together, their adjacent lateral moraines also come together, thus forming a medial moraine in the main or trunk glacier. At the lower part of a

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* The reader is particularly referred, in this connection, to the *Système Glaciaire*, or *Nouvelles Études*, of Mr. Agassiz.

glacier the moraines are often seen elevated somewhat above the general surface of the ice, presenting thus the appearance of a ridge or spine. This arises from the fact that the rocks and earth protect the ice beneath from the action of the sun, and thus prevent that reduction by melting to which the unprotected surface is subject. This *ablation* amounts to from three to four inches per diem in the summer. In like manner, a single flat rock will so protect the ice beneath it, while the unprotected surface all around, sinking away, leaves the rock perched high upon a column of ice. Mr. Forbes gives a fine example of one of these glacier "tables" where a block 23 feet long, 17 feet wide, and 3½ feet thick, was poised on a column of ice 13 feet high, this apparent elevation having been produced in 37 days.

Crevasses are fissures or rents made in the solid ice at those places where, by unequal straining of the mass, the glacier is subjected to a tension too great for the ice to bear. Such tension is occasioned by a change in the slope of the bed, from one part being obliged to move faster than another, or by pressure, as will be noticed hereafter. The crevasses vary in size, from a few inches wide and a few yards long, to many feet in width, hundreds of feet in length, and very great depths. When the glacier passes over a steep incline, the ice is so rent and shivered as to be quite impassable, presenting a confused mass of icy pyramids. Large glaciers, when but little inclined, have little crevassing. Such masses as the Bossons, on the other hand, are magnificently rent and fissured. The crevasses are extremely useful to the observer, as showing by their position the manner in which the strain has acted, thus revealing the mechanics of the glacier; and also as giving an opportunity of examining the interior of the mass for many feet below the surface. The more compact and brittle the ice, the sharper are the crevasses. Those of the *névé* are large and irregular. The plates accompanying the *Études* of Professor Agassiz give the best idea of the different forms of these fissures, although stereoscopic views are sometimes more effective in producing the peculiar sensation which is excited in the Alpine traveller when he *feels* the crevasse beneath his feet. There are many other less important ex-

ternal phenomena, all of which are carefully described in the later works of Professor Agassiz.

To answer the question, how a body so rigid and solid as ice can *move* through a long, crooked valley, in many cases of very slight inclination, bending around the mountain spurs, and almost flowing like a river, is what we require of the glacial theory. What is the force capable of producing such results, and what is the physical quality of the glacier which allows it to obey this force ? Notwithstanding the known fact of motion, even as late as 1840 no person had by careful measurement ascertained either the quantity or the quality of the movement. Some persons had judged of the quantity by the varying position of the lower extremity of the glacier; but this is evidently incorrect, since the motion of that point is a compound phenomenon produced by the real advance on the one hand, and by the melting away of the ice on the other. If the forward motion is equal to the melting, the glacier will appear stationary; and it will apparently advance or retreat as the real motion or the melting away predominates.

The actual data obtained from exact measurements regarding glacial motion are not very extensive; still, they give us enough to deduce with certainty the prominent laws of progression. For precise figures upon this point we are indebted to Agassiz, Forbes, and Tyndall. In September, 1841, Mr. Agassiz commenced the first rigorous operation for ascertaining the motion of a glacier. The example selected was the Lower Aar, which is not only one of the largest in the Alps, but presents nearly all of the phenomena in the most perfect manner, without being distorted by excessive development of any particular feature.* A little below the junction of the two grand affluents, six holes, each ten feet deep, were bored

* The Lower Aar glacier occupies a deep valley, and is composed of two grand affluents, — the Finsteraar descending from the Finsteraarhorn, and the Lauteraar, which is chiefly fed by the snows of the Lauteraarhorn and the Schreckhorn. At the junction it is upwards of 1,500 metres wide, half-way down 1,200, and at the lower end it suddenly contracts from 850 to 580 metres. The length of the lower or trunk glacier is 8,000 metres. The surface is inclined about two degrees at the upper end, four degrees in the middle portion, and eight degrees at the lower part. The extreme lower end falls off more rapidly, however, being inclined nearly forty-five degrees.

in the same straight line across the glacier, and at each of these points a wooden stake was driven into the ice. In July, 1842, the exact displacement of these stakes was measured, with the following result: —

Number of Stake.	Motion in Metres.	Motion in Feet.
1	37.50	125*
2	62.85	210
3	73.65	246
4	80.50	269
5	67.50	225
6	48.00	160

Stake No. 1 was near the Lauteraar side, No. 2 about the middle of the Lauteraar affluent, No. 3 on the Lauteraar side of the medial moraine, No. 4 near the Finsteraar side of the medial moraine, No. 5 about the middle of the Finsteraar affluent, and No. 6 near the Finsteraar shore. This measurement — one of the most complete and satisfactory ever made, since it included so long a period (ten months) and embraced the whole width of the glacier — showed at once both the quantity and the quality of the movement; demonstrating the prime fact that the centre moved much faster than the sides.† In 1841, Mr. Agassiz also fixed the position of five large blocks at such points upon the medial moraine as to embrace nearly the whole length of the glacier. The displacement of these blocks, measured the following year, 1842, showed plainly the general slackening of the velocity of motion from the upper to the lower part of the glacier. Besides the line of six stakes laid out in 1841, in the summer of 1842 a second line of seventeen stakes was put across, with extreme care, about midway of the length of the trunk glacier. This line commenced at once to assume a curve convex to the lower

* In the Boston edition of Mr. Tyndall's "Glaciers of the Alps," these figures have been transposed in printing, so as to read 215 feet; 37.50 metres is according to the *Système Glaciaire.*

† The *idea* of a quicker central motion was distinctly stated by Bishop Rendu in his *Théorie des Glaciers de la Savoie*, published in 1841, in which he says, speaking of the different statements made by the Alpine guides: — "The enormous difference between both results arises from the fact that the latter observations were made at the centre of the glacier, which moves more rapidly, while the former were made at the side, where the ice is retained by the friction against its rocky walls."

end of the valley, the mean daily advance of the point of swiftest motion near the centre being 0.19 metre, or 7½ inches. The deflections of this same line were carefully measured during 1842, 1843, 1844, and 1845, the curve becoming each year more convex,* and, besides giving added proof of the quicker central flow, developing another law of the motion; namely, that the apex of the curve, or the point of maximum speed, is not necessarily in the middle of the glacier, but is sometimes on one side and sometimes on the other, being dependent on the form and direction of the valley, and tending constantly to move towards the convex side of the glacier.†

In 1842, Mr. Agassiz caused the position of eighteen several blocks, eight of which were on the medial moraine, and thus *near* the line of maximum velocity, to be accurately fixed. The motion of these blocks was registered for four years. The mean annual progression, with other elements useful for appreciating the value of this investigation, may be stated as below.

Number of the Block.	Annual Motion.	Width of the Glacier.	Distance below the Junction.
1	38.16	....	260
2	74.36	1500	900
5	77.01	1300	1620
8	67.53	1300	2820
10	70.69	1150	4020
11	56.47	1100	5220
15	38.66	850	6850
17	29.51	580	7650

All of the distances are expressed in metres. These results confirm in the amplest manner the deduction from the five

* The onward movement of this line is well shown in Plate IV. of the *Système Glaciaire.* The same plate shows the tremendous force by which the glacier is dragged round the Rothhorn, wrenching and tearing the ice.

† Mr. Agassiz observes, that it is important to regard this "migration of the centre" when the relative speed of the different parts of a glacier is to be determined, and shows by an example how a number of persons, by selecting points at different distances from the shore, might make either the upper or lower part seem to move fastest. The "Migration" is admirably shown in Plate X. of the *Études*, where the medial moraine of the glacier of Viesch is continually deflected from side to side according to the winding of the valley.

blocks before mentioned, that the motion slackens regularly from the upper to the lower part. No. 1 is, so to speak, in the eddy of the promontory where the junction of the two main branches is made, and, not having got fairly out into the current, has but little motion. No. 10 is probably somewhat accelerated by the entrance at that point of a secondary glacier, which, descending the side of the valley, becomes joined to the main trunk. As regards the varying motion in different seasons, Mr. Agassiz states that the maximum speed is in the spring and the beginning of summer, at which time it exceeds the annual mean; and that it slackens towards winter, and falls below the annual mean.

Mr. Forbes commenced his measurements upon the 26th of June, 1842, and continued them at intervals until September 28th of the same season. The field selected by him was the Mer de Glace of Chamouni. Referring the reader to the map of this glacier in the "Travels through the Alps" or in Johnston's Physical Atlas, for a précise idea of the form and size, we only observe here that it is the outlet of the vast snow-fields enclosed by the Mont Blanc group. The Léchaud and Talèfre glaciers unite first, and the compound thus formed soon after joins the Glacier du Géant at the promontory called the Tacul. From this point the main trunk descends about four miles, varying from a half to three fourths of a mile in width, and finally debouches into the valley of Chamouni at the well-known source of the Arveiron.

The first line laid out was a little below the Montanvert hotel, where the glacier is about 2,300 feet wide. The motion and arrangement of points on this line are shown by the figures below; the first column giving the distance in feet from the side of the glacier, and the second column the mean daily motion in inches from September 17th to 26th.

Distance.	Motion.
300	14.8
690	19.8
915	20.3
1095	20.6

These figures show clearly an increasing velocity as we go

from the sides towards the centre. Mr. Forbes also obtained the velocity of two points, one near the side and one near the centre of each of the principal branches, the Léchaud and the Géant; the quicker central flow in each case being apparent. He further measured several points between the upper and lower end of the trunk-glacier, in order to get the relative velocity of the different regions, and concluded thence that the portion near the lower end moved faster than that above.

It was next desirable to know if the bottom of the glacier was retarded by friction against the bed, as well as the sides. Accordingly, in August, 1846, Mr. Forbes placed three stakes in the ice of the lower end of the Glacier de Bois at Chamouni, which terminates in a face inclined about forty degrees. Upon this slope, at elevations respectively of 13, 59, and 143 feet above the base, three points were fixed, of which the motion from the 13th to the 18th of August was, —

Lower point,	13 ft. high,	2.87 ft.;
Middle point,	59 ft. high,	4.18 ft.;
Upper point,	143 ft. high,	4.66 ft.

At about the same time, namely, from the 13th to the 31st of August, Messrs. Martins and Dollfuss made a measurement of the same kind upon the Grünberg affluent of the Aar glacier. Upon an escarpment twelve metres high, two pegs were put into the ice, one being 1.05 metres and the other 9.27 metres below the surface, both being in the same vertical plane. After the interval above named, the lower peg was 0.20 metre behind the upper one. By far the most satisfactory measurement of this kind, however, was made by Mr. Tyndall in 1857. During that season, the Géant glacier presented near the Tacul a wall of ice, almost vertical, 140 feet high. With extreme difficulty and great risk, one stake was fixed at 4 feet, a second at 35, and a third at 140.8 feet above the bottom. After twenty-four hours, the several stakes had moved as follows: —

Lower point,	4 ft. high,	2.56 in.;
Middle point,	35 ft. high,	4.50 in.;
Upper point,	140.8 ft. high,	6.00 in.;

showing, as in Mr. Forbes's measurement, not only that the bottom was retarded, but that the retardation increased most rapidly near the lower part of the ice.

We come now to the more recent measurements upon the surface of the Mer de Glace, made by Mr. Tyndall in the summer of 1857 and the winter of 1859. This observer ran five complete lines across the Mer de Glace, one across the Géant, and one across the Léchaud tributary. The results obtained were well worth the labor expended. In order to place the measurements in such a light as to show at a glance, not only the movement of each line, but also the passage of the point of swiftest motion from side to side, according to the deflections of the valley, we will arrange three of them as below; the star in each line indicating the point of maximum speed.

The fifth line, at *Trélaporte.*

$10, 14\frac{3}{4}, 16, 17\frac{1}{2}, 19\frac{1}{2}, 19, 19\frac{3}{4}, 19\frac{1}{4}, 17\frac{1}{4}, 16, 15\frac{1}{4}, 15, 12\frac{3}{4}, 13\frac{1}{2}, 11\frac{1}{4}.$

*

The fourth line, at *Les Ponts.*

$6\frac{1}{2}, 8, 12\frac{1}{2}, 15\frac{1}{4}, 15\frac{1}{2}, 18\frac{3}{4}, 18\frac{1}{4}, 18\frac{3}{4}, 19\frac{1}{2}, 21, 20\frac{1}{2}, 23\frac{1}{4}, 23\frac{1}{4}, 21, 22\frac{1}{4}, 17\frac{1}{4}, 15.$

*

The third line, at *Montanvert.*

$19\frac{1}{2}, 22\frac{3}{4}, 28\frac{3}{4}, 30\frac{1}{4}, 33\frac{1}{4}, 28\frac{1}{4}, 24\frac{1}{2}, 25, 25, 18, .. 8\frac{1}{2}.$

*

The several numbers represent the daily motion in inches. The right hand of the page is the west, and the left hand the east; the glacier moving towards the bottom. The fifth line abuts at the west end upon the promontory of Trélaporte, which pushes the glacier over to the east, and at the same time we find the point of maximum velocity on the eastern side of the axis. At the fourth line, the spur called Les Echellets pushes the whole mass back to the west, forcing it into the bay beneath Les Ponts; and at the same time the point of maximum velocity recrosses to the west of the axis. But hardly is the glacier embayed beneath Les Ponts, when it is again forced off to the east by the Montanvert, and the line of maximum speed for the third time crosses the axis, and is found east of the centre line of the glacier. Here what Mr. Agassiz calls the "migration of the centre" is shown in

the most perfect manner. The line traversed by the point of maximum velocity is thus, as described by Mr. Tyndall, " a curve more deeply sinuous than the valley itself, and it crosses the axis of the glacier at each point of contrary flexure."

The measurements of the same observer also give us valuable information regarding the relative motion of the glacier at the different regions, from the source down. The width of the Glacier du Géant at the Tacul is 1,134 yards, and the maximum velocity 13 inches per diem. The Léchaud tributary is 825 yards wide above its junction with the Talèfre, and its maximum speed 9½ inches per diem. The Talèfre tributary has a width of about 638 yards. The total width of the three branches is thus 2,597 yards; the whole of which is squeezed at Trélaporte through a channel 893 yards wide, at a maximum velocity of 19¾ inches per diem.

To ascertain if the same conditions of motion obtained during the winter as in summer, Mr. Tyndall measured one line 80 yards above and another 130 yards below the Montanvert, in December, 1859, with the following result. The maximum on the upper line was 15¾ inches per diem, against about 30 in summer at the same place. The second line showed a maximum of 17½ inches, the summer maximum at the same place being about 35. The swiftest point was also in both cases removed from the centre.

On the small and shallow glaciers lying upon the flanks of mountains, and inclined from fifteen to fifty degrees, measurements have shown that the centre moves faster than the sides, and the top faster than the bottom; but the absolute velocity is much less than that of the large, but slightly inclined glaciers. Where the small masses descend far enough to reach a trunk-glacier in the main valley, abut upon it, and become connected with it, the velocity is checked by the opposing mass in front, so as to be less at that point than nearer the source; but when such glaciers are not opposed by any resistance in front, the velocity is greatest at the lowest portion.

With the exception of a few detached observations, we have now placed before the reader all of the actual field-work illustrative of the quantity of glacial motion. We shall find

hereafter somewhat regarding the quality of motion without making any direct measurements. Before going further, we may lay down the following simple deductions from equally simple experiments. 1. The central part of all glaciers moves faster than the sides. 2. The surface of the glacier moves faster than the lower portion. 3. The point of maximum speed does not necessarily traverse the axis of the glacier, but departs from it according to the form of the valley, moving always towards the convex side of the glacier. 4. The greatest variation in motion is near the sides and near the bottom. 5. The velocity of the Lower Aar glacier decreases regularly from the upper to the lower region, the width decreasing always in the same direction. 6. The Mer de Glace increases in velocity from the upper to the lower end of the trunk-glacier, the width decreasing regularly. 7. The winter motion is slower than that of summer, but the relative motion of the different parts remains constant.

We come now to a portion of our subject far less defined than the preceding, and one upon which observers differ not only upon matters of principle, but upon matters of fact. We refer to the physical nature of the ice of glaciers, — to the quality of the mass, by virtue of which it is enabled to obey the force impressed upon it, and to move. Let us see what phenomena are presented to us in the different regions of the glacier.

All forms of snow fall on the high Alps, flaky, granular, and powdery, the particular form depending upon meteorologic conditions. Great flakes do not fall unless the temperature is above freezing and the weather calm; but let a cold wind arise, and it becomes at once fine and powdery. A combination of the grains produces the elegant forms often seen. The snow does not long preserve its primitive form. As soon as the sun melts the superficial crystals, those next below absorb this moisture, these again when saturated communicate it to their lower neighbors, and the water-soaked grains freeze, round and transparent. This is the *névé;* and this change takes place in the fields of New England as well as among the Alps of Switzerland. All kinds of snow change to *névé*. The time necessary for this transformation depends upon

atmospheric circumstances. Mr. Desor saw a layer of dry, powdery snow a foot deep changed completely into *névé* in a day. Mr. Agassiz considers this operation a new crystallization. The surface water, he says, penetrating the snow, finds there a finely crystalline mass; one part of these crystals is melted by it, the other part becomes the foundation for the *névé* grains. The larger grains appropriate the water produced by the meeting of the smaller ones. The conditions required are a temperature high enough to cause this partial melting, but not enough to reduce all of the snow to water. By light watering we can make an artificial *névé;* but if we pour on too much water, it runs through to the lower part and freezes there. The spring crust in New England is frozen *névé;* the true *névé* is below it, a dry, granular, incoherent mass of icy particles. As melting goes on, these grains increase in size, and finally become cemented together, thus producing a sort of conglomerate ice, in which the original *névé* grains are plainly visible, the intergranular spaces being filled with an opaque aerated ice, which melts away when exposed to the sun, leaving the grains as they were before cementation. This conglomerate is less dense than ordinary ice, of a dull white color, and having a certain toughness (*terne et coriace*, Agassiz). The *névé* ice is, however, but a superficial phenomenon; the effect of cold in freezing the grains together is not felt to any great depth. As we descend into the mass of the *névé*, the ice becomes more compact and transparent, less aerated, and, in fine, more like true glacial ice. It is consolidated by the immense pressure of the mass above, — an operation which can be imitated by an hydraulic press, in which we may consolidate damp snow to a slab of clear ice.

As regards the real compact ice of the lower glacier, Mr. Agassiz gives us the following.

"The real glacier ice is a different thing from the ice of rivers; it develops by an insensible passage from the *névé*. It is more compact, shows no trace of granular structure, the air is collected into little bubbles, while the ice between the bubbles is perfectly transparent. It is traversed by a network of capillary fissures, by means of which water infiltrates to great depths into the glacier. These fissures divide the mass into irregular angular fragments, varying in size from

half an inch in the upper part to three inches in diameter in the lower regions of the glacier. When these capillaries are full of water, they are not easily seen; but when the water is drained off and the air occupies its place, they are quite plain, and the ice becomes more opaque. When filled with water, they give the ice a certain plasticity, which, so long as the water is not frozen, causes it to be of a loose nature; a knife-blade may even be introduced into the mass without separating the pieces."

Mr. Forbes observes: —

"The glacier ice is eminently fragile. This condition depends upon the ice being traversed by an infinity of capillary fissures, generally invisible, but which become distinctly seen whenever the ice is exposed to sudden changes of temperature. The glacier consists of a series of tightly wedged polyhedrons, of the most irregular forms, often three inches or more in length, and of which a bunch may be held connectedly together until by melting they become disengaged. But while the pieces remain thus connected, the fissures impart to the mass a certain rude flexibility within small limits. Hence a glacier is not a mass of solid ice, but of ice and water, more or less yielding according to its state of wetness or infiltration." *

Regarding the origin of the fissures, Mr. Agassiz in his earlier work attributed them to the compression of the air-bubbles; but in his later volume he substitutes for that explanation "the pressures and tensions consequent upon the variations of temperature." While the ice remains granular, he says, infiltration goes on regularly through the mass; but when the ice, becoming compact, loses the granular structure, this infiltration is arrested; and when the water thus entrapped freezes, it splits the ice. This new fissure again fills and freezes, and produces new cracks, and so on until the network is complete.† In proof of the existence and character of these capillaries, Mr. Agassiz gives the detail of experiments made upon pieces of ice taken from various depths on the Aar gla-

* "I therefore freely admit, what I formerly doubted, that a glacier is penetrated in summer to a great depth by water, which saturates all its pores." — Forbes, *Travels through the Alps*.

"Le glacier est comparable à une immense éponge." — Agassiz.

† "La congélation de l'eau absorbée, produit ainsi dans toute la masse du glacier, une tension excessive, qui, etant plus ou moins inégale, occasionne une multitude innombrable de fêlures, ou fissures capillaires, lesquelles s'étendent en tous sens et se croisent sous les angles les plus divers." — Charpentier, *Essai*, p. 12.

cier, with colored liquids, which were infiltrated through the capillaries. These experiments are admirably illustrated in the plates to his later work. The same observer says: "If we take a piece of the most transparent ice from the bottom of a crevasse, and place it on a rock, we shall see the capillary fissures appear first on the surface and then gradually spread downwards to the base. If we then turn it over and water it, they will disappear. The block will be transparent so long as it is soaked."

Strikingly in contrast with the preceding are the conclusions of Messrs. Tyndall and Huxley as given by the former,* where the experiments of Mr. Huxley with colored liquids upon the ice of the Mer de Glace so failed to discover the fissures, that Mr. Tyndall writes: "Thus the very existence of these capillaries is rendered so questionable, that no theory of glacier-motion which invokes their aid could be considered satisfactory"; — an observation, however, which does not accord with a remark upon page 163 of the same work, where the author states that an examination of the structure of the ice of the Allelein glacier taught him that it was composed of an aggregate of small fragments, and that, where the ice was partially weathered, the surfaces of division between the fragments could be traced through the coherent mass. In a paper upon "Some Physical Properties of Ice," by Mr. Tyndall,† he speaks of examining a piece of ice which he found "traversed by hazy surfaces of discontinuity, which divided the apparently continuous mass into irregular prismatic segments." Again, in a paper "On the Veined Structure of Glaciers," ‡

* The Glaciers of the Alps, p. 339.

† Philosophical Trans., Vol. CXLVIII. [1858,] pp. 211-227.

‡ Phil. Trans., Vol. CXLIX. [1859,] p. 279. Besides the extract above, this paper contains the following: — "From the constitution which the foregoing observations assign to glacier ice, this disintegration seems natural. The substance is composed of fragments which are virtually crystallized in different planes; and it is not to be expected that the union along the surfaces, though they may be invisible when the ice is sound, is as intimate as that among the different parts of a mass homogeneously crystallized. Besides, ice no doubt, and all uniaxial crystals, expands by augmentation of temperature differently in different directions, and hence a differential motion of the particles on both sides of the above surfaces, when the volume of the substance is changed by heat or cold, is unavoidable. Such surfaces would then become surfaces of discontinuity, and perhaps produce that granular condition which has occupied so much attention."

he says of a piece of ice from the Allelein glacier: "On reference to Mr. Agassiz's figure, it will be quite manifest that we are dealing with the same phenomenon." (As indeed it is from his sketch.) "We have the division of the ice into angular fragments," &c. And subsequently, in the same paper, he says: "The ice of glaciers is sometimes disintegrated to a great depth, causing it to resemble an aggregate of jointed polyhedra more than a coherent solid." Mr. Huxley, in a letter to Mr. Tyndall, says: —

> "It is a remarkable feature of glacier ice, that it is liable to weather in a peculiar manner, becoming fissured and breaking up into irregular fragments to a certain depth; that at eight or ten inches deep the ice always appears smooth, glassy, and without the least trace of fissures, but the superficial portion is separated by very obvious fissures, so fitted into one another as to cohere with some firmness." *

Notwithstanding the above, Mr. Huxley concludes with the remark, that not one of Mr. Agassiz's experiments affords the slightest evidence that capillary fissures are a primitive and essential constituent of the structure of the deep ice of a glacier. Mr. John Ball, however, writes: "Pending further observations, which I trust Mr. Huxley may be induced to make, I shall venture to adhere to the belief that the irregular network of fissures which pervades the surface of the ice when exposed to air and warmth, represents a structure already existing in the ice before it came to the surface; and that former fissures, although possibly closed so as to show no trace under the microscope, may yet be surfaces of easy melting, which on the first application of heat are recalled into existence." † Mr. Agassiz says, that, in moving the rocks of a moraine, we generally find the ice smooth, dark, and compact, showing no trace of fracture; that, after being exposed a few moments to the light and heat, the fissures appear and show the angular fragments; but that, on again covering the ice, the fissures vanish. Peculiar conditions doubtless render the fissures apparent or non-apparent; and though we may

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* Phil. Mag., 1857, Vol. XIV. p. 241, "The Structure of Glacier Ice."

† Phil. Mag., Vol. XIV. [1857,] p. 481, "Observations on the Structure of Glaciers."

not be able to assign the cause of their formation, or to say what part they play in glacial physics, the fact of their existence does not, we think, admit of doubt.*

The color of the ice depends upon the quantity of air mixed with it, in the shape of small bubbles, being more blue and dense as the bubbles are expelled, and more white as the bubbles are numerous; just as blue water becomes white by beating it into froth, thus mixing it with air. The form and position of these bubbles, as described by Mr. Agassiz, would seem to be an index to the forces which have acted on the mass of the glacier. He describes them as round or ovoidal at the surface and in the higher regions, but as flattened and compressed both in the depths and in the lower regions of the glacier, where the ice is most compact. But the most remarkable fact is, that while the bubbles in a single angular fragment are all flattened in the same direction, in two adjoining fragments the direction will be entirely different. Each angular fragment has thus its system of bubbles, and its direction in which those bubbles are flattened. Mr. Agassiz states, that at depths of over two hundred feet he has found these bubbles almost flat, similar to those above, and that in fragments from a great depth all the bubbles without exception are strongly flattened. It would seem from the observations of Mr. Tyndall, who has looked at the intimate structure of

* Professor Erman of Berlin, in a letter to Mr. Tyndall, published in the Philosophical Magazine, Vol. XVII. p. 405, [1859,] on the structural division of ice observed on Lake Baikal, in Siberia, describes it as divided into hexagonal prisms.

General J. G. Totten, U. S. A., read a paper before the American Association for the Advancement of Science, in August, 1859, (Am. Jour. Sci., Vol. XXVIII. p. 359,) on the dissolution of the ice of our Northern lakes, in which he says: "The ice broke up in a single night, and next morning was found in the shape of prismatic fragments, of which the length was equal to the thickness of the mass of which they had been a part. The sides of the fragments were irregular as to size and form, the breadth or thickness varying from $\frac{3}{4}$ to $1\frac{1}{2}$ inches in the same prism. Examination then and afterwards of floating fresh-water ice has shown that the natural effect of the advancing year is gradually to transform ice, solid and apparently homogeneous, into an aggregation of the irregular prismatic crystals, standing in vertical juxtaposition, having few surfaces of contact, but touching at the edges."

In the Am. Jour. Sci., Vol. XXIX. p. 111, [1860,] Mr. Charles Whittlesey, of Cleveland, Ohio, presents a paper on the dissolution of field ice, in which he describes a cube of Lake Superior ice, thirty inches to the side, disintegrating in half a day to a mass of triangular and rectangular prisms. The planes of division he supposes to have existed in the solid ice as the result of the crystallization in freezing.

ice more closely than any other glacialist, that two phenomena have been confounded by Mr. Agassiz under the head of air-bubbles. All observers agree in finding cells in glacial ice containing air and water, the former floating as a little bubble in the latter; but to Mr. Tyndall we owe the discovery of the real nature of the more frequent and more important phenomenon, the vacuum disks. These are small cavities formed by internal liquefaction, and they strongly resemble flattened bubbles,* but in reality are only the decomposing of the original crystallization of the ice. Such disks always lie in planes parallel to the plane of freezing. They are formed in all kinds of ice. Now Messrs. Agassiz, Tyndall, Huxley, Ball, and all other observers, agree in the fact that these disks are arranged in groups, and that, while all the disks of each group are flattened in the same direction, no sort of parallelism exists between the direction of the disks of different groups. These groups are the angular fragments of Mr. Agassiz, although the separating fissures, as before noticed, are not always visible. This explanation, though to a certain extent † removing the need of accounting for the different pressures which were supposed to have flattened the bubbles, demands instead the cause of the varying positions of the planes of freezing. Although Mr. Tyndall developed the disks by sending a condensed beam of sunlight into a piece of lake ice, they are found equally perfect under glacial moraines, and in places where no light can come. This, however, is not surprising, since they seem to be an essential constituent of the ice, and only await the proper conditions to become developed.

* Glaciers of the Alps, pp. 353 - 361; also Phil. Trans. Roy. Soc., Vol. CXLVIII, [1858,] pp. 211 - 227.

† We say *to a certain extent;* for Mr. Tyndall remarks, that the compound air and water cells are also flattened in the direction of the apparent flattening of the disks. Phil. Trans., Vol. CXLIX. p. 279.

The simple distortion of bubbles does not, perhaps, indicate the pressure which might be inferred; since we may see in the blocks of ice left at our doors in the morning bubbles apparently drawn out to long cylinders, the direction of the length being perpendicular to the plane of freezing. We have seen the small bubbles in a glass jar, filled with frozen water, so drawn out as to resemble fine silver threads, a fourth of an inch long, and inclined at different angles, but all pointing towards the axis of the jar. We are indeed surrounded by phenomena the most wonderful, which only await the opening of our eyes to be clearly seen.

The next important feature which presents itself is the veined or ribboned structure, or the blue bands. We find in almost every part of all glaciers the general mass of white ice traversed by narrow and tolerably regular bands of a clear, blue, transparent ice. Upon tracing these bands until we come to a crevasse, we see that they penetrate to great depths, and are, in fine, laminæ of a more dense and less aerated ice, standing generally at a high angle, and cropping out upon the surface of the glacier. They vary from less than a tenth of an inch to several inches in thickness, and from one foot to many yards in length. They are dislocated by crevasses, as stratified rocks are by faults. They are sometimes parallel with and sometimes transverse to the length of the glacier, sometimes straight and sometimes curved, in some places very close and frequent, and in others almost wanting. Mr. Agassiz attributed the existence of these bands to the freezing of water in previously formed fissures. Mr. Forbes at first supposed them to have the same origin, the fissures being formed by the differential motion of the ice; but he afterwards rejected the freezing of the water, as observation showed the internal glacial temperature to be too high to allow this, and considered the fissures to be reunited "by the simple effects of time and cohesion." He subsequently, however, substituted for this a new cause, which, as well as the explanation of Mr. Tyndall, will be noticed soon.

Upon no portion of glacial physics has there been greater difference among observers than with regard to stratification. All agree that certain horizontal beds occur in the regions of the *névé;* but Mr. Agassiz alone maintains that this primitive bedding continues under different forms throughout the whole extent of the glacier. It appears to us that several distinct phenomena have been confounded by observers under the head of stratification. In his later work Mr. Agassiz says: —

"When we climb to some height above a glacier, we see on its surface a series of lines shaped as more or less sharp curves; they are found in all glaciers without exception, and when we have once got their form from a distance, nothing is easier than to trace them. If now we descend on to the glacier, we perceive that the sand or gravel which renders them visible is attached to a continued fissure, which

gives place on the edges of the crevasses to a band of compact ice, mixed with this same gravel, which often penetrates to a great depth. It is thus evident that it is not the sand, but the fissure, which constitutes the essential fact. Now when we give particular attention, we remark, as well on the surface as in the crevasses, similar fissures, but not all containing the same quantity of foreign bodies. It is those containing the most that Mr. Forbes calls dirt-bands. These bands are not, as he thinks, the effect of unequal disintegration of certain parts of the glacier; they attach to the interstices of the beds, which gain the surface in the order of their succession, and under different angles."

In 1842, Mr. Forbes thus described the "Dirt-Bands" of the Mer de Glace: —

"One afternoon I happened to ascend higher than usual above the level of the Mer de Glace, and was struck by the appearance of discolored bands traversing its surface. These shades, too indistinct to be noticed when near or upon the glacier, except upon very careful inspection, are very striking and beautiful when seen at a distance, by a light not too strong. There are evidently bands of dirt upon the surface of the ice, having nearly the form of very elongated parabolas merging in the moraines on either side."

These bands Mr. Forbes first considered due to alternate sections of hard and soft ice, the latter retaining the dirt, but the former being washed clean by rains. Mr. Tyndall, however, showed that in this Mr. Forbes mistook the effect for the cause; since the grains of sand and gravel which formed the "Dirt-Band," by absorbing the solar heat, melted into the ice, and gave it a false appearance of porosity. Indeed, Mr. Forbes himself, in a later publication, says distinctly, that the bands are due to mechanical causes alone, and to no variation of internal consistency. Mr. Tyndall also plainly points out the cause of these bands, and thus enables us to dismiss them at once as a local phenomenon. They are produced by the periodical breaking of the back of the glacier as it goes over an ice fall, thus dividing the mass below into a series of ridges and hollows, which latter receive the dirt blown on to the glacier. Finally, as the whole mass descends, the ridges are toned down, so that little except the bands of dirt are left, and the quicker flow of the central part curves these to the parabolic form described by Mr. Forbes. The ice-fall is upon the

Géant tributary, and it is to that branch, even after confluence, that the bands are confined. Notwithstanding, therefore, that Mr. Agassiz seems to consider his dirt *lines* the same thing as Mr. Forbes's dirt *bands*, it is sufficiently evident that they are quite distinct. The bands are many feet in width, the lines only a few inches; the bands are superficial and local, the lines general and integral. The lines of Mr. Agassiz are simply the outcropping of highly inclined thin beds of compact ice mixed with sand and gravel, and according to him separating the original beds of stratification.

From what has preceded, it will be seen that the thin beds of dense ice thus described have much in common with the blue bands. Each is seen by its outcropping on the surface as a narrow band of ice more compact than the surrounding mass; each is seen in the crevasses to be highly inclined, and to reach to great depths; and they are found generally to be parallel to one another. On the other hand, according to Mr. Agassiz, the beds are found in all parts of the glacier, are regularly spaced, extend over great distances, and contain the sand and gravel before mentioned; the bands, on the other hand, are confined to certain regions, are not equally spaced, do not extend continuously over long distances, and rarely contain foreign bodies. Mr. Agassiz is the only person who has observed the beds; all have observed the bands. The outcropping of the beds is represented on the surface as a line a few inches wide of compact ice. These lines near the source of the glacier cross nearly straight from side to side; but lower down, from the quicker central flow, they become curved, the apex of the curve corresponding to the point of maximum velocity. A glacier formed of two or more branches will show two or more systems of these curved lines, side by side, though after a while the curves combine. The physiology of motion is admirably shown in the Lower Aar glacier, which below the Abschwung is composed of fourteen affluents, each having its own system of contour lines, besides four small tributary glaciers from the right bank, each bringing down its contours at right angles to the motion of the trunk-glacier.

The inclination of the structure, whether we call it beds or bands, is an important feature. All observers agree in find-

ing the angle at which these thin laminæ stand, large (even vertical) in the middle region of the glacier, and less as the lower end is approached. Mr. Agassiz gives the inclination of the structure of the Lower Aar, a little below the junction of the grand affluents, as from 85 to 90 degrees, and as regularly flattening till at the lower end it is only 20 degrees. The same thing is recorded by all observers upon all glaciers; and the change is accounted for by the friction of the ice against the bottom, which retards the lower part, while the upper portion moves on unimpeded. This seems reasonable; but the fundamental difficulty, as Mr. Agassiz justly calls it, is to account for the vertical position in the start. In the *névé* the strata must be, and are known to be, horizontal; the question is, How can they change from that position to vertical, when the tendency is to produce a directly opposite result? Except Mr. Agassiz, we believe all deny the permanence of the original stratification, and thus relieve themselves from answering this question; and even he acknowledges the extreme difficulty of tracing the structure from the *névé* to where the vertical bedding or veining first appears. Of course we cannot be expected to admit the change from simply seeing the horizontal beds of the *névé* and the vertical bands of the middle glacier. We demand some intermediate steps in the process. These Mr. Agassiz professes to give us. He shows us a well (*puit*) 16 metres deep, near the confluence of the two main branches, in which at different depths we see the thin beds of compact ice inclined about 30 degrees, while at a few hundred yards below the angle is nearly 90 degrees, or vertical. There are reasons why this evidence is not satisfactory. First, we are told that nearly at the same point the general inclination is from 85 to 90 degrees; next, that perhaps there is no glacier where the angle does not vary from 20 to 90 degrees, and that not only in great distances, but from one bed to another; and, finally, that even the same bed varies considerably as we observe it at the sides or the summit of the arc. Mr. Agassiz himself says: "I have seen in the chevrons of the Lauteraar an example where the summit was inclined 20 degrees, while the sides at ten metres' distance were at an angle of 60 degrees."

We do not think that the observed facts warrant the belief that the beds *are* less inclined above the middle region of the glacier; and until this is clearly proved, it seems hardly worth while to search for the cause of such a variation. There is another objection to believing the beds in the lower glacier to be a modification of the *névé* stratification. The horizontal layers observed in the upper regions by all who have examined the glaciers are in no place represented as more than one or two feet deep; while, if the lines of compact ice drawn upon the plan of the Lower Aar by Mr. Agassiz show the planes of separation of the annual beds, these layers would be nearer five hundred feet thick.*

Mr. Agassiz observes, that in the upper part of glaciers we can count the *névé* beds as far down the crevasses as we can see. Mr. Forbes says, that below a very small depth, compared to the vast vertical sections exposed in some places, the *névé* stratification disappears, the interior of the mass being granular, and without structure of any kind. Messrs. Agassiz, Forbes, and Tyndall all give examples where the horizontal bedding and the blue bands, nearly vertical, occur in the same place. No person except Mr. Agassiz distinguishes the thin beds of compact ice, containing sand and gravel; the only structure remarked by other observers being the blue bands. The strongest fact against the permanence of the original stratification is, that when a glacier is broken entirely to pieces, sometimes even to powder, by going over a precipice, as in the Rhone Schwartzwald and La Brenva, the blue bands come out as fresh as ever below the fall, in a nearly vertical position, as soon as the ice consolidates by pressure. Mr. Agassiz considers this reformation of structure as confirming the idea of the continuance of the original bedding, and as showing an inherent tendency in the ice to stratify; but here we believe the Professor is quite at fault, since the structure which ap-

* Mr. John Ball observes (Phil. Mag., Vol. XIV. [1857,] p. 481, Suppl.): "The *névé* strata cannot represent annual beds, because they are in some cases only six or eight inches deep; while, to account for the average annual fall of sixty feet, they should be as much as eight feet thick." He concludes that the beds represent each considerable fall of snow, but not *annual* deposits; and he thus accounts for the varying depth, and the different degrees of glacification observed.

pears below the ice-fall is plainly vertical blue bands, and no horizontal stratification at all.

We should bear in mind, that our real knowledge is extremely small as to the depths of a glacier. All of our theories of the structure and physiology of these vast bodies of ice, it may be over a thousand feet deep, are founded upon what we can see in the upper five or ten per cent of that depth. Now the measurements show the chief part of the retardation upon the surface to be near the shore; analogy would lead us to infer a similar action near the bottom; so that, as we may have a line almost straight in the middle of a wide glacier, but very much curved near the sides, so we might have a vertical line from the top to near the bottom. Indeed, the holes called *moulins* are sensibly vertical to great depths; and yet Mr. Tyndall's measurements show that they partake of the general movement of the glacier. Mr. Forbes observes that the upper part may remain almost unaffected by the movement (i. e. unaffected by any differential motion in the vertical plane).

Having now seen somewhat of the observed data, let us look at the different theories which have been proposed to account for the motion of glaciers. If the mere search for truth had been the actuating force which has moved the several investigators in this matter, the task of reviewing their labors would be simple. In the outset, this doubtless was the end proposed; the temptation, however, to digress in order to obtain personal reputation, and the pleasure of knocking over the theory of a fellow-laborer, added to a desire to reap the harvest in the shape of a completed solution of the problem, rather than to sow the seeds by a careful collection of data, has prevented that cordial co-operation among the leading glacialists which ought always to be found among philosophers. The object of reviewing the labors of the distinguished men whose names are connected with the subject before us, is to show the part which each has taken in furnishing a correct theory of glacier motion, and is in no way intended to express their present views, inasmuch as some of them have long since withdrawn from active labor in this department. We must not tie an observer too closely down to his own

writings. In commencing a new study, we have to assume much, and we use terms as we can best apply them. Even if our assumptions are proved wrong, and our terms have been misapplied, they have yet been useful. A rude and imperfect theory often furnishes the stand-point from which we collect and arrange our data. Astrology, Cosmogony, and Alchemy were the forerunners of Astronomy, Geology, and Chemistry. We are not to blame for *putting forth* crude ideas, but for *retaining* them. An impartial investigator will see what *is*, sooner than what he *desires*. He will not look at Nature with a vision distorted and a mind prejudiced by favorite opinions. He will endeavor to bring his mind into harmony with Nature, and when he has done this, he can read aright the broad volume she has spread out before him. We hope, in what follows, to treat the several authors who have contributed to the establishment of the glacial theory with the utmost impartiality. Such at least is our intention.

Scheuchzer, a Zurich savant, in 1705 advanced the theory that the motion of glaciers was produced by the freezing of infiltrated water, which, by dilating and thus enlarging the whole mass, caused the glacier to move in the direction of least resistance, namely, down hill. Altmann and Grüner, in 1760, supposed that the glacier slid down its inclined bed from the effect of gravity. This theory was accepted by the great Alpine naturalist, De Saussure of Geneva, in 1799. He also believed the motion to be aided by the lubrication of the bed over which the glacier slid, by means of water obtained from the melting of the ice in contact with the soil. Hugi — author of *Naturhistorische Alpenreise* — believed the motion due to an interior labor (*travail*) of the glacier. Jean de Charpentier, Director of Mines in the Canton Vaud, embraced the dilatation theory of Scheuchzer. Agassiz also attributed the motion to the dilatation of water infiltrated into the mass, in his earlier work (*Études*, 1840); but near the close of his later work (*Système*, 1847), he says that each of the agents which has been considered the chief cause has part in producing the motion; that the slope of the bed is a condition of progression, but that it does not determine the speed; that the plasticity of the ice is another condition, not

less essential, since it allows a body like ice to move over very gentle slopes; and he concludes by saying that dilatation comes in as a motive force, when the plasticity is reduced to a minimum. Bishop Rendu of Annecy, in 1841, without putting forth any one theory as correct, proposes in the form of questions all of the different explanations, not even excepting the semi-fluid doctrine of Mr. Forbes, published two years later.* Since observation has shown that glaciers move in the severest winters, and that the internal temperature of the mass is not low enough to freeze the infiltrated water, we need not occupy ourselves with the theory of dilatation. Further, as great inclination has little or no effect on progression, and as the rudest examination is sufficient to repel the idea that a rigid mass of ice can slide through a crooked valley, we may dismiss the explanation which relies upon sliding. We have remaining the theories of Forbes and of Tyndall; which we proceed to examine.

In 1843 Mr. Forbes published his "Travels through the Alps," containing the viscous theory, as it has been called, of glacier motion, which is thus defined by its author: —

"My theory of glacier motion is this. A glacier is an imperfect fluid, or a viscous body, which is urged down slopes of a certain inclination by the mutual pressure of its parts. The sort of consistency to which we refer may be illustrated by moderately thick mortar, or the contents of a tar-barrel, poured into a sloping channel. The extremes of viscosity are perfect fluidity and perfect rigidity. A body may be viscous enough to move under great pressure, which alone would stand still. When the semi-fluid ice inclines to solidity, during a frost, its motion is checked; if its fluidity is increased by a thaw, its motion is instantly accelerated. Its motion is greater in summer than

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* "Marche-t-il ensemble comme un bloc de marbre sur un plan incliné? Avance-t-il par parties brisées comme les cailloux qui se suivent dans les coulois des montagnes? S-affaisse-t-il sur lui même pour couler le long des pentes comme le ferait une lave a la fois ductile et liquide? Les parties qui se détachent vers les pentes rapides suffisent-elles à imprimer du mouvement à celles qui reposent sur une surface horizontale? Je l'ignore. Peut-être encore pourrait on dire que dans les grands froids l'eau qui remplit les nombreuses crevasses transversales du glacier venant à se congeler prend son accroissement de volume ordinaire, pousse les parois qui la contiennent, et produit ainsi un mouvement vers le bas du canal d'ecoulement." — Rendu, *Théorie des Glaciers de la Savoie*, p. 93.

in winter, because its fluidity is greater. The motion does not cease in winter, because the winter's cold penetrates the ice only to a limited extent. The veined structure is a consequence of the viscous theory. Any particle, in a fluid or semi-fluid mass, urged by a force from above, does not necessarily move in the direction in which the force impels it; — it moves *diagonally:* forwards, in consequence of the impulse; upwards, in consequence of the resistance directly in front; — thence a series of surfaces of separation rising towards the surface, varied in curvature by the law of the velocity of the different layers of the glacier. Near the head of the glacier, where the resistance in front is enormous, the separation planes will be highly inclined; as the lower end is approached, the frontal resistance continually diminishes, and the line of least resistance becomes more and more horizontal; finally, when the lower end is reached, the planes fall away altogether, and the upper layers roll over the lower ones. The crevices formed by the forced separation of a half-rigid mass, whose parts are compelled to move with different velocities, are united by the effect of time and cohesion, and thus produce the blue bands."

The mean daily lowering of the glacial surface in summer varies from three to over four inches. In one hundred days this would amount to about thirty feet.* Notwithstanding this, the absolute height does not vary much from year to year, so that this ablation must in some way be compensated, otherwise the glacier would taper out to a wedge.† This compensation Mr. Forbes makes by the swelling of the lower part of the glacier by compression. He considers the resistance to motion as increasing from the upper to the lower regions, on account of accumulating friction. The ice is thus squeezed forward and upward against the mass in front, producing a condensation longitudinally, and a consequent swelling upward, — an effect evidently exactly opposed to the reduction of the surface by melting. Whether this explanation is correct or not can be decided only after we have some

* The large glacier table shown in the frontispiece to Mr. Forbes's "Travels" was elevated thirteen feet in thirty-seven days, from June 30 to August 6, four and a quarter inches per day; or rather the general surface of the glacier was reduced by that amount.

† Suppose the Mer de Glace to be four miles, or about twenty thousand feet long, and to move five hundred feet per annum, the surface being reduced thirty feet each season. A given point would be forty years in moving the length of the glacier, in which time it would have melted down no less than twelve hundred feet.

extended and careful levels from a fixed bench-mark to the surface of the ice, in connection with the observations on the relative motion of the different regions upon the same glacier, besides a record of the reduction of the surface at different points.

Mr. Forbes illustrated his theory by models made of plaster and glue, so mixed and colored as to show the internal details of the motion of the mass under different conditions. The results obtained from the models show plainly that in a plastic mass the centre moved faster than the sides, that the top moved faster than the bottom, that a retardation in front resulted in a swelling upwards, and that alternate layers of white and blue paste assumed somewhat the form of the blue bands in a glacier; namely, curved from shore to centre, and inclined less and less as the lower end was approached. From the analogy thus established between the glacier and the model, Mr. Forbes concluded that the ice was a viscous mass, urged onward by the mutual pressure of its parts.

There has been much dispute as to what constitutes the theory of Mr. Forbes; but, if we understand his writings, it is that *the cause of glacier motion is the viscosity of glacier ice.* We should not wish to confine Mr. Forbes too closely to his own term, *viscous*, especially as he seems disposed in his later works to substitute *plastic.* Indeed, if the theory rests upon the viscosity of ice, we should have only to show that in no instance whatever has it been found to possess the qualities which would entitle it to this term, and the theory would vanish, leaving Mr. Forbes as a simple observer who has furnished a few facts, and not as a contributor to the explanation of the cause of glacier motion. If, however, he is content to have discovered that glaciers have a quality so far equivalent to viscosity as to allow the quasi semi-fluid motion, we can easily accept this, and can plainly allow him a good share in the solution of the glacier problem. It has been said that Mr. Forbes's theory does not depend on a word, but that it is "a compendious epitome of a multitude of observed facts," and that it is "the congeries of facts which he has observed." We are aware of no person who tries so hard to make it depend upon a word as Mr. Forbes himself, yet with-

out giving a very definite meaning to that word. *Viscous* is defined as *sticky*, *adhesive*, *glutinous*, *tenacious; plastic*, as *capable of being moulded*. According to these definitions, although ice may be plastic, it can in no way be called viscous. As to Mr. Forbes's theory being a collection of observed facts, we might as well call the astronomical data furnished to Newton the law of gravitation. Certainly no amount of facts can ever constitute a theory. It is only when, by co-ordinating the observed data, we rise above phenomena to causes, that we can be said to have reached a theory in any science. Mr. Forbes has labored harder to find analogies between glaciers and really viscous bodies, than to ascertain the true nature of glacial ice. It is hard to learn from his writings what he does believe. Making all due allowance for papers written disconnectedly during the course of ten years, the statements in his "Occasional Papers" are, to say the least, puzzling. For example, in the "Summary of Evidence adduced in favor of the Plastic or Viscous Theory of Glacier Motion," we have the following: — "A glacier is not a mass of solid ice, but a compound of ice and water more or less yielding according to its state of wetness or infiltration." "A glacier is not coherent ice, but a granular compound of ice and water." "It is clearly proved by the experiments of Agassiz and others, that the glacier is not a mass of ice, but of ice and water; the latter percolating freely through the crevices of the former to all depths of the glacier." "The water in the crevices does not constitute the glacier, but only the principal vehicle of the force which acts on it." "If it were not for the capillarity of the ducts, it is plain that no effective hydrostatic pressure would be developed at all." "The function of the infiltrated water seems to be that of preserving the whole ice in that state of softness which immediately precedes its dissolution, as well as of conveying hydrostatic pressure." Speaking of the motion of the Mer de Glace, he writes: "It took no real start, until the frost had given way, and the tumultuous course of the Arveiron showed that its veins were again filled with the circulating medium to which the glacier, like the organic frame, owes its energy." From the above, we should say that Mr. Forbes considered

water essential to the glacial structure; but in the same volume he says: "I have nowhere affirmed the presence of liquid water to be a *sine qua non* to the plastic motion of glaciers." And also: "The ribboned structure presented by all glaciers appears to be the only true essential structure which they possess. The existence of granules divided by capillary fissures, as well as of large crevasses, are equally unessential to glacial structure." "A glacier is not a mass of fragments. As the analogy of the glacier to a river in which the fluid principle is greatly in defect, and the cohering or viscous principle is greatly in excess, is the theory which I maintain, it is evident that the analogy of a stream of sand or loose materials shot from a cart, or any other comparison with an aggregate of incoherent fragments or individual masses, must be wrong, if mine be right. And I feel confident, not only that such an incoherent mass could not move after the manner of a glacier, but also that attentive inspection of a glacier at once contradicts such an idea." Mr. Forbes has a most convenient mode of reconciling the seemingly most contradictory statements under the comprehensive remark, that viscosity ranges all the way from perfect fluidity to perfect rigidity. Under such definition, of course, glacial ice, as well as glass, is viscous. Thus, whatever we find regarding the nature of ice, we must at least admit the so-called theory to be sufficiently viscous.

The fact that a glacier moves generally as a semi-fluid mass no more proves ice to be a semi-fluid, than the fact that a wooden beam obeys the same general law of deflection as a cast iron beam proves wood to be a crystalline substance. Beside the measurements of Mr. Forbes showing the quicker central and surface motion, the only fact he has given to indicate analogy between a glacier and a semi-fluid mass, or, as he expresses it, the plasticity of ice on a large scale, is the putting a straight line, ninety feet long, divided by small pins into forty-five equal spaces, upon a compact and well-developed portion of the Mer de Glace. These stakes, as might have been supposed, after some time took the form of a regular curve, showing that the ice moved continuously and uniformly, and not by sudden rending at any points. It seems to us, however, that, if Mr. Forbes's explanation of the veined

structure is correct — the facts, we think, show the contrary — his own observations would furnish the plainest possible proof that glacial ice is eminently brittle; inasmuch as he repeatedly states, that the smallest, slowest, and most regular motion cannot take place without splitting the ice; which certainly would not be the case in a gluey, sticky, tenacious, adhesive mass. But though his explanation of the veined structure, not being correct, does not thus demonstrate the fragility of the ice, the formation of crevasses does prove glacial ice to be totally devoid of tenacity, as may plainly be seen by the following results of observation.

So long as a glacier moves over a uniformly inclined bed, it is not unequally strained, and it remains unbroken by crevasses; but if it pass from a flat slope to a steeper one, the surface is subjected to tension, and it splits. A viscous or pasty mass could pass over the brow of a hill without fracture; but the slightest change of inclination, if convex upwards, will rend the glacier. Mr. Tyndall gives us the following facts. The Mer de Glace below Trélaporte passes from an incline of 4° to one of 9° 25′ (on the surface of the ice), the difference or change of inclination being only 5° 25′; and yet the ice, in passing over this great angle of 174° 35′, is so crevassed as to be impassable. It is also shown, that a certain part of the same glacier by its motion would be obliged to stretch only seven tenths of an inch in five hours; and yet it cannot do this, but breaks. Mr. Tyndall also illustrates the inability of the ice to change its form without fracture. He writes: "Let the sides of this page represent the boundaries of the glacier at Trélaporte, and any one of its lines of print a transverse slice. Supposing the line to move down the page as the slice of ice moves down the valley, then the bending of the ice in twenty-four hours would only be sufficient to push forward the centre in advance of the sides by a very small fraction of the width of the line of print. To such an extremely gradual strain the ice is unable to accommodate itself without fracture." He further says: "A boss of rock, a protuberance on the side of the flanking mountain, anything, in short, which checks the motion of one part of the ice, and permits an adjacent portion to be pushed away from it, pro-

duces crevasses."* Mr. Agassiz observes that all crevasses, of whatever form or position, are the effect of a common cause, — tension overcome; and that every crevasse is formed perpendicularly to the plane of the tension.†

We think it sufficiently evident from the preceding, that ice is anything but viscous. The next question is, Does it possess any quality equivalent to viscosity? The temperature at which ice melts is generally stated to be 32 degrees Fahrenheit. Experiment, however, has shown that it softens sensibly at four degrees lower, or at 28 degrees. From this Mr. Forbes concludes, that, since the general internal temperature of a glacier is from 28 to 32 degrees, the ice is kept in a just melting condition, in the same manner as wax softens before it melts. Mr. Tyndall has cooled ice down to 100 degrees below the freezing-point, when he found it so hard as to resist a knife; and he observes, that although ice at 28 degrees may be called soft in comparison with that 100 degrees colder, it is the softness of calcareous spar in comparison with rock crystal, rather than that of melting wax, honey, or tar; and he concludes by saying: —

"How far this ice, with a softness thus defined, when subjected to the gradual pressures exerted in a glacier, is bruised and broken, and how far the motion of its parts may approach to that of a truly viscous body under pressure, I do not know. The critical point here is, that the ice changes its form and preserves its continuity during its motion, in virtue of *external* force. It remains continuous whilst it moves, because its particles are kept in juxtaposition by pressure; and when this external prop is removed, and the ice, subjected to tension, has to depend solely upon the mobility of its own particles to preserve its continuity, the analogy with a viscous body instantly breaks down."

It is a well-known fact, that water subjected to a strong pressure requires a greater degree of cold than usual to freeze it, or, conversely, that heat is developed by pressure;‡ so that

* This is admirably shown in Mr. Agassiz's map of the Lower Aar glacier, where the ice is dragged around the angle of the Rothhorn, near the Pavillion; and also in Pl. VIII. Fig. 10, of the *Système*.

† Regarding the mechanics of crevasses, the reader is referred to Mr. Tyndall's book, pp. 315–327; and to Mr. Hopkins's papers in the Philosophical Magazine, Vol. XXVI. (1845).

‡ Tyndall, *Glaciers of the Alps*, p. 349. Mousson, *Bibliothèque Universelle*, Vol. III.

a body of rigid ice may have those parts subjected to a severe pressure liquefied, and frozen again when the pressure is removed. Further, Mr. Faraday has shown that two pieces of ice with moistened surfaces, at a temperature above 32 degrees, when placed in contact, will freeze together. This property boys employ in making snowballs, and they well know that moist snow is necessary; dry snow will not answer. Mr. Tyndall applied this principle to a most interesting series of operations upon masses of ice. With a series of boxwood moulds, he showed experimentally that hard crystalline ice could be forced into any shape by pressure, the change of form being produced by breaking and recongealing. He says: —

"The ice, in changing its form from that of one mould to that of another, was in every instance broken and crushed by the pressure; but suppose that instead of three moulds three thousand had been used, or, better still, suppose the curvature of a single mould to change by extremely slow degrees, the ice would then so gradually change its form that no rude rupture would be apparent. Practically the ice would behave as a *plastic* substance."

May we not now conclude that, although ice can in no way be called viscous, it has a quality equivalent thereto to a degree sufficient to account for the quasi semi-fluid motion exhibited by glaciers, namely, plasticity, this latter characteristic being the result of fracture and regelation?

The veined or ribboned structure (blue bands) already noticed completes the solution of the problem. Mr. Agassiz considered this feature as a phenomenon more or less superficial, but still of great importance as a means of facilitating the infiltration of water into the mass. Mr. Tyndall observes that it is not to be regarded as a partial phenomenon, or as affecting the constitution of glaciers to a small extent merely. Mr. Forbes says that it is the intimate structure of the glacier, and the only one which it possesses. These bands are extremely useful as indices to the motion of the ice at different places, being dislocated, contorted, and inclined according to the forces acting upon the mass. The structure is stated, by

[1858,] p. 296. James Thomson, *Phil. Mag.*, Vol. XIV. [1857,] p. 548. Wm. Thomson, *Phil. Mag.*, Vol. XVI. [1858,] p. 463. Tyndall, *Phil. Trans.*, Vol. CXLIX. p. 279.

all glacialists, to be found perpendicular to the pressure at the place where it is produced. We have already seen the earlier explanations given to account for the bands. We have now to examine the latest opinion of Mr. Forbes. The fundamental idea is this. The veined or ribboned structure of the ice is, he says, the result of internal forces, by which one portion of the ice is dragged past another, in a manner so gradual as not necessarily to produce large fissures in the ice and the consequent sliding of one detached part over another, but rather the effect of a *general bruise* over a considerable space of the yielding body. This *bruise*, reconsolidating by pressure, gives birth to a blue vein. Thus the differential motion is supposed to be the cause of the structure; and, according to Mr. Forbes, the veins are best developed where the differential motion is a maximum. He also says, that the bands are least distinct near the centre, for there the difference of velocity of two adjacent strips, parallel to the length of the glacier, is nearly nothing; but that, where two glaciers come together, the structure immediately becomes more developed, which arises from the increased velocity as well as friction of each, due to lateral compression. For all this, while admitting the general course of the central structure upon the Lower Aar to be parallel to the length, he observes that it is extraordinary, if its production is to be attributed to the remote influence of the retaining walls of the glacier. We do not see why Mr. Forbes should charge it to this remote influence, when, according to his own theory, it might be attributed either to the increased velocity and friction at the junction of the two main branches, or to the differential motion at the adjacent sides of the branches before the junction. The *experimentum crucis* of Mr. Forbes is the glacier of La Brenva, in which a particularly fine development of structure occurs at a point where the ice is forced obliquely against a rocky promontory, and where the differential motion is shown, by measurement, to be considerable. We apprehend, however, that an example of structure equally good may be found where there is no differential motion, but simply pressure. Mr. Hopkins has plainly shown that the lines of greatest

strain in a glacier, moving down a valley of uniform width, extend from the shore obliquely forty-five degrees down stream, and that the crevasses are at right angles to this line ; also that the lines of greatest compression extend from the shore obliquely forty-five degrees up stream, and that the blue bands are developed at right angles to this line ; that is, at the sides of the glacier the crevasses point from the shore up stream, and the blue bands down stream. Now this is the same direction that Mr. Forbes would have them assume from differential motion, although he has never shown, and we believe cannot show, that differential motion ever takes place in this direction. But he also says : "These bands are formed where the pressure is most intense, and where the differential motion of parts is a maximum." From this, it might be due either to the pressure or the motion, if it were not for a structure which occurs where no differential motion can, on any theory, occur, but pressure only. Mr. Tyndall gives us the following : "Where the inclination of a glacier suddenly changes from a steep slope to a gentler, the ice to a certain depth must be thrown into a state of violent longitudinal compression. At such places a structure is developed transverse to the axis of the glacier. The quicker flow of the centre causes this structure to bend more and more, and after a time it sweeps in vast curves across the entire glacier." In this manner the marginal structure may be brought into the direction often observed, namely, oblique from the shore down stream, in those places where pressure to form it in that position is lacking. This transverse structure may be seen upon the Strahleck affluent of the Lower Grindelwald, the Rhone, and the Talèfre fall in that branch of the Mer de Glace of Chamouni. All observers agree in finding the structure *to be made* only where there is strong pressure ; after being formed, it may be transferred, by the motion of the ice, to places where there is no pressure. Mr. Forbes alone maintains the influence of differential motion, although the only motion of that kind which has ever, by measurement upon a glacier, been proved to exist, is parallel to the shore, which is not the direction ever assumed by the true marginal structure.

We cannot judge of the production of the veined structure in all cases by its occurrence; for it is often found in places which have no part in its formation. The vertical longitudinal structure in the great Aletsch glacier, opposite the Märjelen See, was formed eight miles above that point, by the lateral pressure from the tributary glaciers which come in at right angles to the trunk. Mr. John Ball asks, How can this structure, which must have been formed two hundred years ago, have withstood the reduction of the surface by melting, which at only ten feet per annum would be two thousand feet? If we say, by swelling, caused by the slower motion in front and the accumulation behind, we shall find a question equally hard to answer, namely, How can a compression sufficiently great to produce this swelling act without obliterating the old structure and producing a new one in a transverse direction? We have no measurements of any amount upon this immense glacier.

Mr. Tyndall supposes the varied structure to be produced by pressure acting at right angles to the plane of the veins, such pressure causing internal liquefaction; the water thus produced freezing when the pressure is removed. Mr. Agassiz confirms this explanation to a certain extent, since he says: "The bands are most frequent at the confluence of many affluents, and also where the ice is more compact than elsewhere; for example, at the Aar glacier it is where the ice is submitted to the strongest pressure, arising from the junction of the two grand affluents. This correlation between the compactness of the ice and the frequence of the bands is confirmed by the other fact, that the bands first appear where the ice has already a certain compactness." The final proof of the correctness of the pressure explanation of the veined structure is furnished by the experiment of Mr. Tyndall, who actually produced blue bands in small pieces of common ice, by subjecting them to pressure; such bands being at right angles to the force applied. Careful examination of the ice during the operation showed the internal liquefaction taking place.* We have already seen how a mass of ice may change

* See Phil. Trans., Vol. CXLIX. [1859,] p. 279, Paper on the Veined Structure of Glaciers, by Mr. Tyndall, or "The Glaciers of the Alps," p. 409, for the detail of this most conclusive and interesting experiment.

its form by fracture and regelation. By the blue bands we learn that the internal liquefaction produced by intense pressure, which Mr. Tyndall so plainly illustrated in his laboratory, actually takes place in the glacier on a large scale; thus allowing a slight change of form, and furnishing the moisture necessary for the refreezing of the separated portions of the ice in a new position, when the pressure is removed.

Mr. Tyndall does not claim to be the founder of a glacial theory; but his book is concluded by what he calls a partial summary, which is in fact a most complete, concise, and correct statement of all we know regarding the nature of the glaciers. Briefly it is as follows. Glaciers are derived from mountain snow, which is consolidated by pressure to ice. The power of yielding to pressure is possessed by the most compact ice. The motive power is the weight of the upper glacier, which by settling squeezes out the lower parts, which yield in the direction of least resistance and move downwards. This motion is accomplished partly by sliding, and partly by the yielding of the mass. This yielding takes place by fracture and regelation, which actions produce an effect equivalent to plasticity. The ice can yield thus to pressure, but not to tension. The result of stretching is the crevasses, which are marginal, transverse, or longitudinal; — the first being produced by the oblique strain consequent upon the quicker central flow, the second by the passage of the glacier over a convex vertical angle, and the third by pressure from behind and resistance in front, which causes the mass to split at a right angle to the pressure. The veined structure is produced by compression, resulting in internal liquefaction. The water thus produced is refrozen when the pressure is removed, forming a blue band. The structure occurs in three forms, which may be regarded as complementary to the crevasses, namely, marginal, transverse, and longitudinal, being in each case developed at right angles to the pressure.

The cause and office of the angular fragments, the flattening of the bubbles, the disappearance of the original stratification, the permanence of structure through many years of ablation, and the causes of the increase and decrease of gla-

ciers at the present time, are questions upon which future glacialists have ample opportunity to exert themselves.

Before concluding, we wish to say a word regarding the division of the credit due for the establishment of the glacial theory; partly that it may be understood to whom we owe our information on this subject, and partly because great injustice has been done by nearly all writers to one of the most distinguished as well as indefatigable observers. No person has devoted so much time to the collection of actual data in the field, nor furnished us with such accurate plans, and so complete and long continued measurements, as Professor Agassiz, and yet there seems, with the single exception of Mr. Tyndall, a determination, particularly in England, to ignore altogether his services.* The solution of the problem, as we view it, has consisted of three parts; — the field operations, showing the nature of glacier motion; the study, both in the laboratory and in the field, of the physics of ice; and the application of the physical principles evolved to the explanation of the observed facts of progression. Professor Agassiz laid out in 1841 the work which, remeasured in 1842, demonstrated the quicker

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* "I believe I may safely affirm, that not one observation of the rate of motion of a glacier, either on the average or at any particular season of the year, existed when I commenced my experiments in 1842." — Forbes, *Travels through the Alps*, p. 38.

"Mr. Agassiz continued some of these annual measures, but only in a rough way, by causing his guides to reckon the distance of a block on the moraine by lengths of a pole or rod from a fixed rock some thousand feet off. These measures appear not to have been altogether trustworthy." — Forbes, in *Encyclopædia Britannica*, in 1855.

Mr. Forbes should have known that the very complete measurements of Mr. Agassiz, made in 1841 and 1842, were published in the *Comptes Rendus* in 1842.

"But even the melancholy pleasure of refuting himself was denied to the Swiss *savant*. In science the race is not unfrequently to the swift; and the Northern philosopher, having betaken himself to Switzerland, in June, 1842, was enabled, by applying the delicate and accurate process of theodolitic measurement to the small daily movements of the glacier, to observe in four days the results for which M. Agassiz, with his comparatively rough procedure, had to wait a twelvemonth." — *Westminster Review*, April, 1857.

The author of the above had evidently never seen the later work of Professor Agassiz, nor the *Comptes Rendus* of five years before.

"It is to Professor Forbes alone that we owe the first and most correct researches respecting the motion of glaciers." — *North British Review*, August, 1859.

"The prize for which the Swiss *savans* were contending was carried off by a more skilful and more fortunate competitor." — *Edinburgh Review*, Jan., 1861.

central flow, and the slackening of the motion from the upper to the lower regions of the Lower Aar glacier. Professor Forbes commenced his measurements in 1842, and, by taking the result of a few days only, actually observed the quicker central flow before Mr. Agassiz did. The results of Mr. Agassiz were, however, published before those of Mr. Forbes. The measurements of Mr. Agassiz were much more complete than those of Mr. Forbes, who in no case continued his lines entirely across a glacier. Either of these observers without the other was sure to discover those facts of motion which had been so plainly stated by Bishop Rendu in 1841. The discovery of the quicker surface flow belongs to Mr. Forbes, although the same thing was separately discovered by Messrs. Martins and Dollfuss a few days later. Mr. Forbes, though not the discoverer of the blue bands, was the first to perceive their importance; but his chief merit seems to be the connecting of all the data, and perceiving from this connection the resemblance to semi-fluid action. Beyond that point, his researches have simply supported an incorrect theory, into accordance with which he has endeavored to bend all facts near and remote. Mr. Tyndall has been eminently the physical contributor to the solution of the question, and by a skilful application of Mr. Faraday's Regelation, and the internal liquefaction of Messrs. James and William Thomson and Professor Mousson, has shown *how* the glacier is enabled to obey the force impressed upon it, — how a hard and brittle substance like ice can move like a soft and pasty mass.

The difficulty of judging correctly of what Mr. Forbes calls his theory arises in a great degree from the manner in which he twists his theory round from time to time so as to absorb all subsequent discoveries. He writes in the prefatory note to his Occasional Papers, in speaking of the recent progress of the glacier theory: "If it be granted that the terms 'bruising and re-attachment,' 'incipient fissures united by time and cohesion,' were equivalent in 1846 to the phrase 'fracture and regelation,' applied in 1857, I shall, I trust, still be held to have laid just and solid foundations for a Plastic or Viscous Theory of Glaciers." Now it is exactly this that will not be granted, unless Mr. Forbes renounces entirely and without reserve the

differential motion as a cause of the blue bands. It is to be observed, that in his later writings he shows a decided inclination to use the term *plastic* in place of *viscous*, or at least to consider them as synonymous; but this is simply a misapplication of terms. There is nothing viscous about ice, and there can be no viscous theory of glacier motion.

With regard to glacial literature, the amount of published matter bearing on the subject is large. The works of Charpentier, Agassiz, Forbes, and Tyndall are particularly valuable as including the chief part of the field work. The papers in the *Bibliothèque Universelle* of Geneva, the Edinburgh Philosophical Journal, the Philosophical Transactions, the Philosophical Magazine, and the *Comptes Rendus*, by Agassiz, Forbes, Tyndall, Guyot, Desor, Martins, Hopkins, Whewell, Mallet, and others, are valuable. The *Essai sur les Glaciers*, by M. Charpentier, contains a large amount of observation, is well written, and has a fine map of the valley of the Rhone. The *Études sur les Glaciers*, by Professor Agassiz, should be read by the glacial student, although much of it is superseded by the later work of the same author. Its admirable plates deserve particular attention. The *Système Glaciaire*, or *Nouvelles Études*, of Professor Agassiz, is the most extended of all works on this subject, and contains more facts than all the other writings together. The text is accompanied by an atlas of plates, illustrative chiefly of the topography and physics of the great glacier of the Aar. Professor Forbes, besides the "Travels through the Alps of Savoy" and the "Occasional Papers," is author of a work entitled "Norway and its Glaciers," and also of the papers in the last edition of the Encyclopædia Britannica, and in Johnston's Physical Atlas, upon Glaciers. For a brief and popular, but thoroughly philosophical view of the several theories, with an exposition of physical principles which for method and clearness cannot be excelled, and for the journal of a most dauntless mountaineer, the book of Professor Tyndall has never been surpassed. There is only one thing better than the book, and that is — travelling in the Alps.